Optical MEMS for QIP applications

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2/23/2006

Outline

- Sandia MEMS technology –SUMMiT V
- Layout of current mirror array/mirror structure
- Mirror performance
  - Static
  - Dynamic
  - Optical (Mirror Figure)
  - ZEMAX model of effect of mirror figure on system performance
- Some improved switching speed results
- Mirrors for QIP
- Conclusion

Optical MEMS at Sandia

Primary Technology:

SUMMiT V with BEOL metallization

(Some III-V, SOI, etc.)

Projects Include:

- MEMS mirrors for optical beam forming (free space true time delay implementation)
- MEMS mirrors for hyper spectral imaging (Hadamard Transform Spectral Imager)
- MEMS mirrors for fiber optic cross connect for diagnostics and state-of-the-health monitoring (OPAL)
- MEMS mirrors for adaptive optics (Ultra-Light Weight Next Generation Telescope)

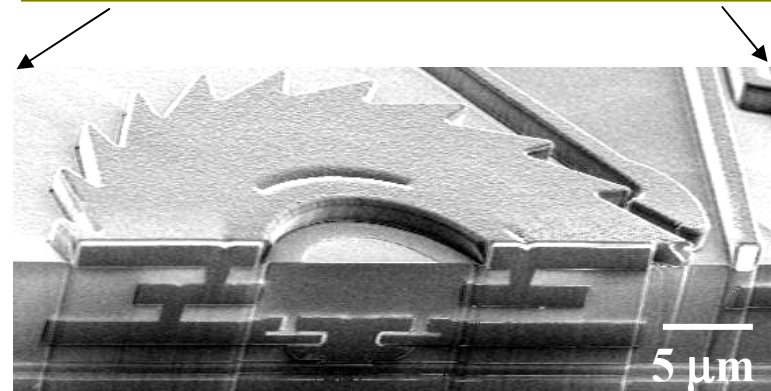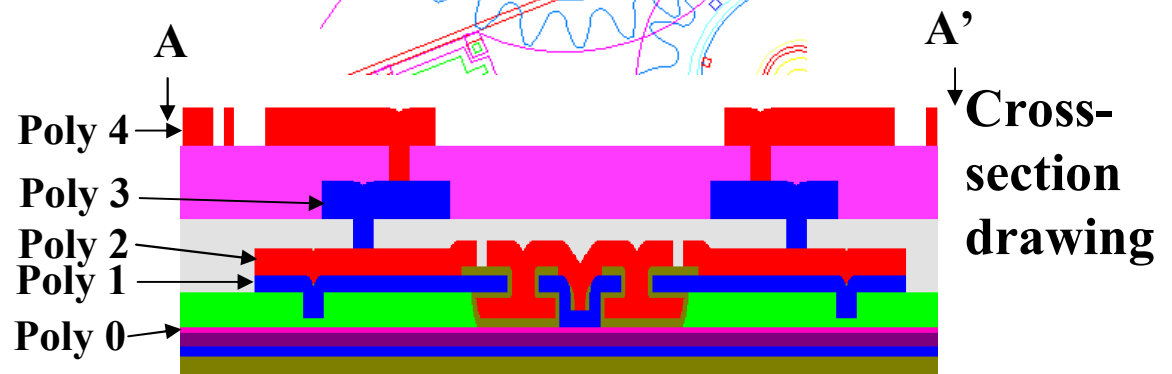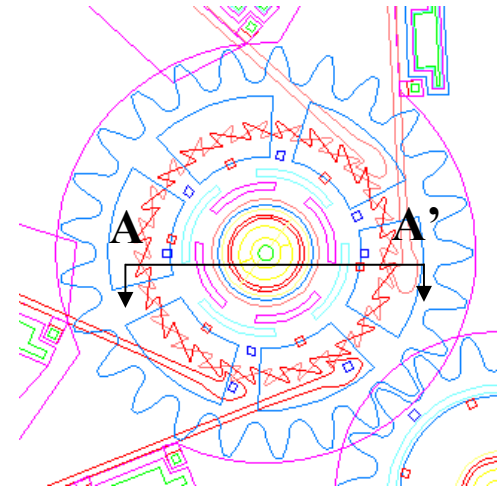No real attempt yet to integrate electronics and optical MEMS…but study is ongoing

2 × 5 array

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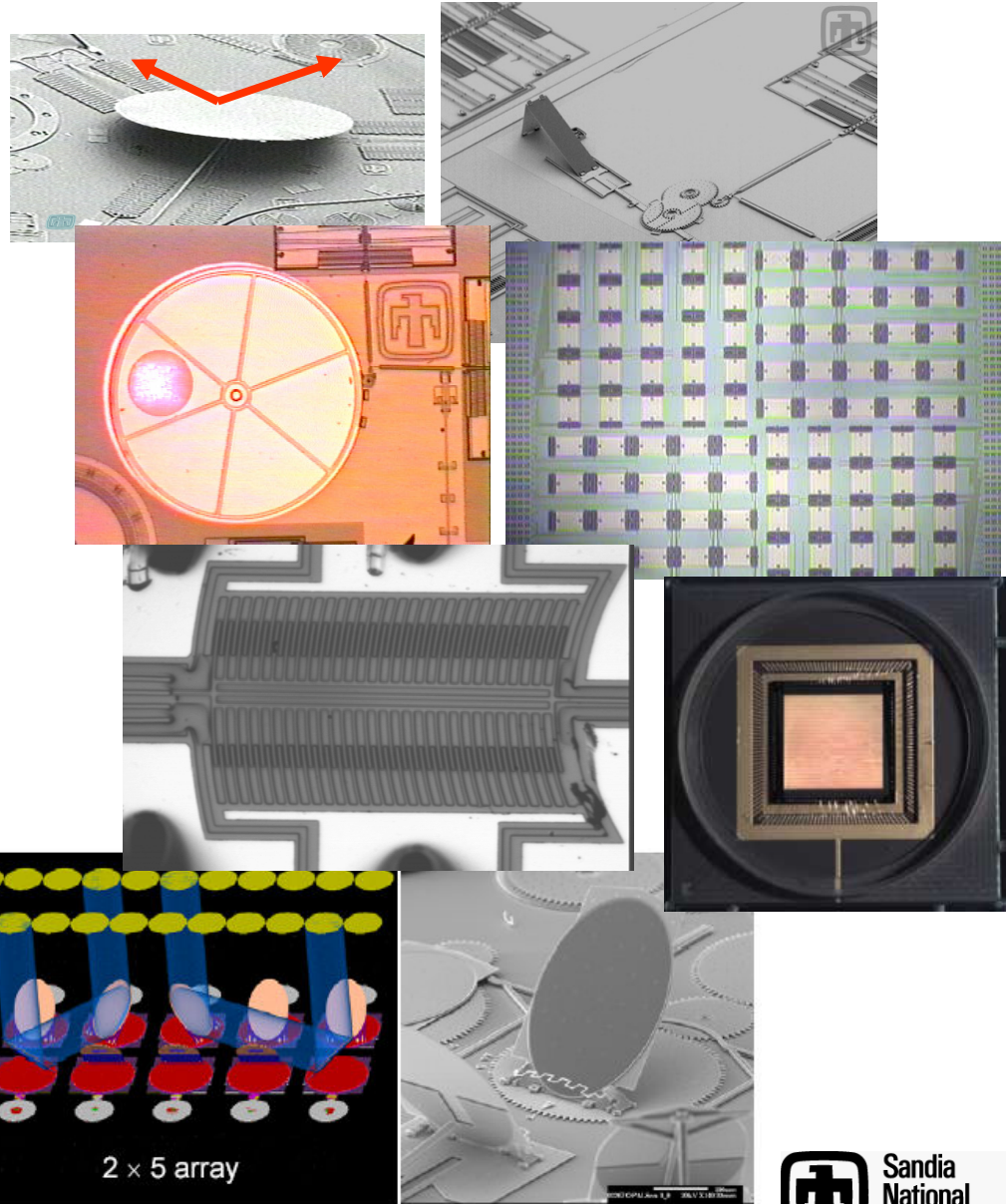
SUMMiT V™ Technology

Process features

- Polycrystalline silicon (Poly)
- Low stress (< 5 MPa)
- Conformal depositions
- high fracture strength (~ 3 GPa)

- Ground plane layer (Poly 0)
- 4 structural levels
    - (Poly 1 - Poly 4)

- Chemical Mechanical Planarization (CMP)
- 1 µm design rule

- Technology accessible through SUMMiT foundry (SAMPLES)

- Custom BEOL specific to this program
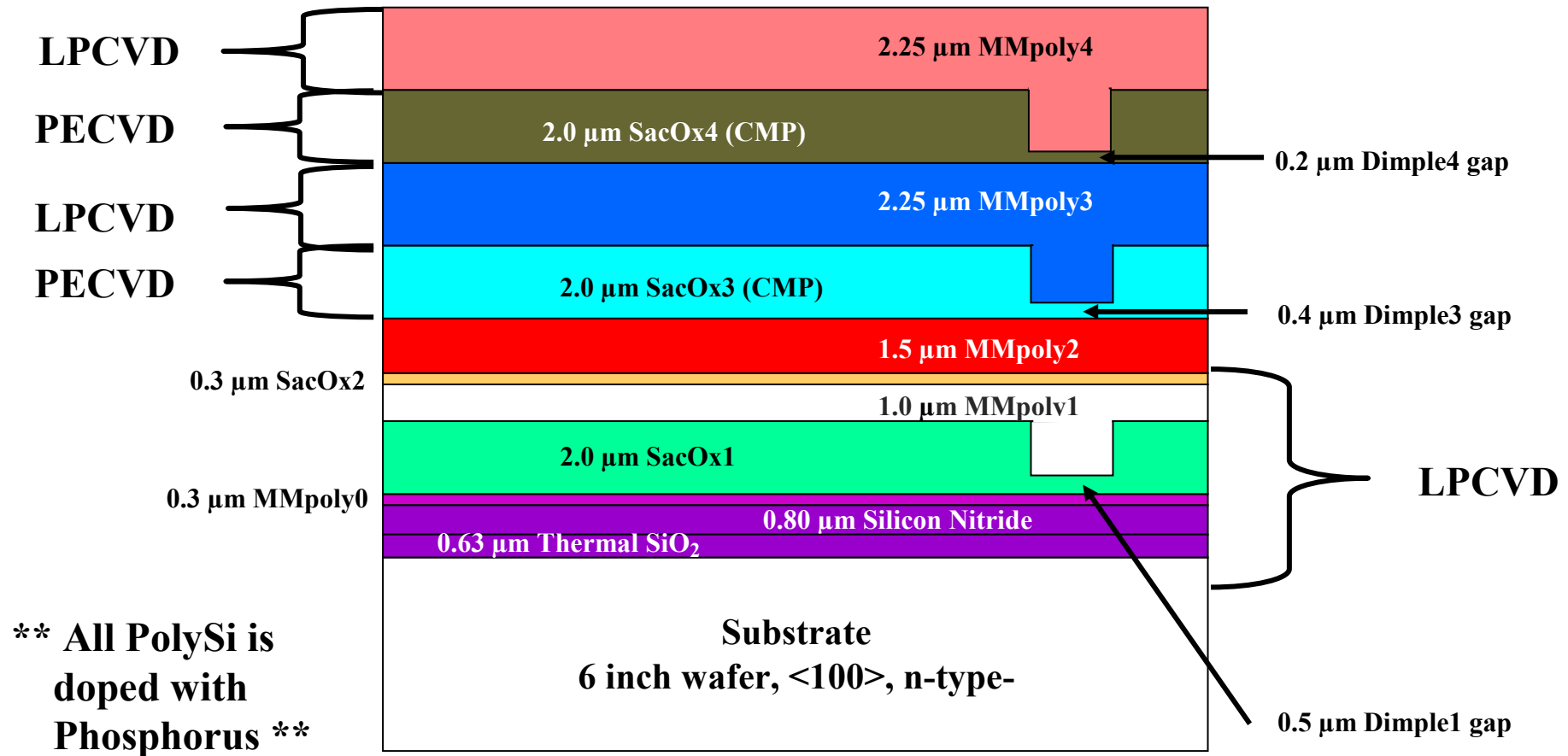   - metallization
    - packaging

Design

A — A'

Cross-section drawing

A — A'

Poly 4
Poly 3
Poly 2
Poly 1
Poly 0

FIB cross-section

5 µm

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SUMMiT V™ - Sandia Ultra-planar Multi-level MEMS Technology

LPCVD

PECVD

LPCVD

PECVD

2.25 μm MMpoly4

2.0 μm SacOx4 (CMP)

0.2 μm Dimple4 gap

2.25 μm MMpoly3

2.0 μm SacOx3 (CMP)

0.4 μm Dimple3 gap

1.5 μm MMpoly2

0.3 μm SacOx2

1.0 μm MMpolv1

0.3 μm MMpoly0

2.0 μm SacOx1

LPCVD

0.80 μm Silicon Nitride

0.63 μm Thermal SiO$_2$

Substrate
6 inch wafer, <100>, n-type-

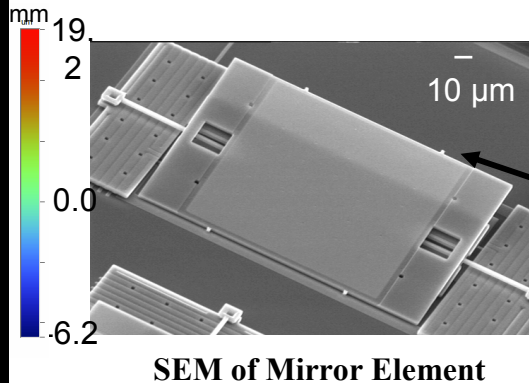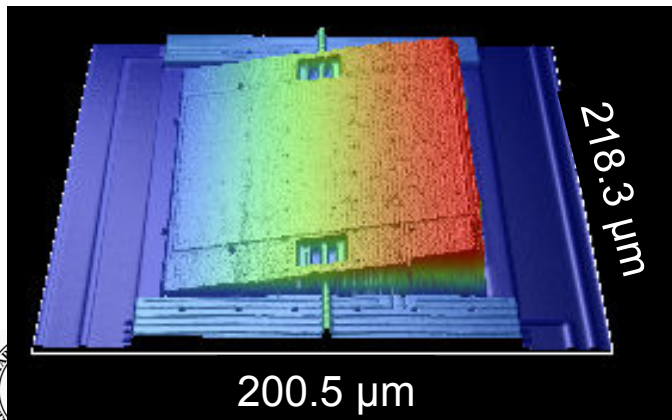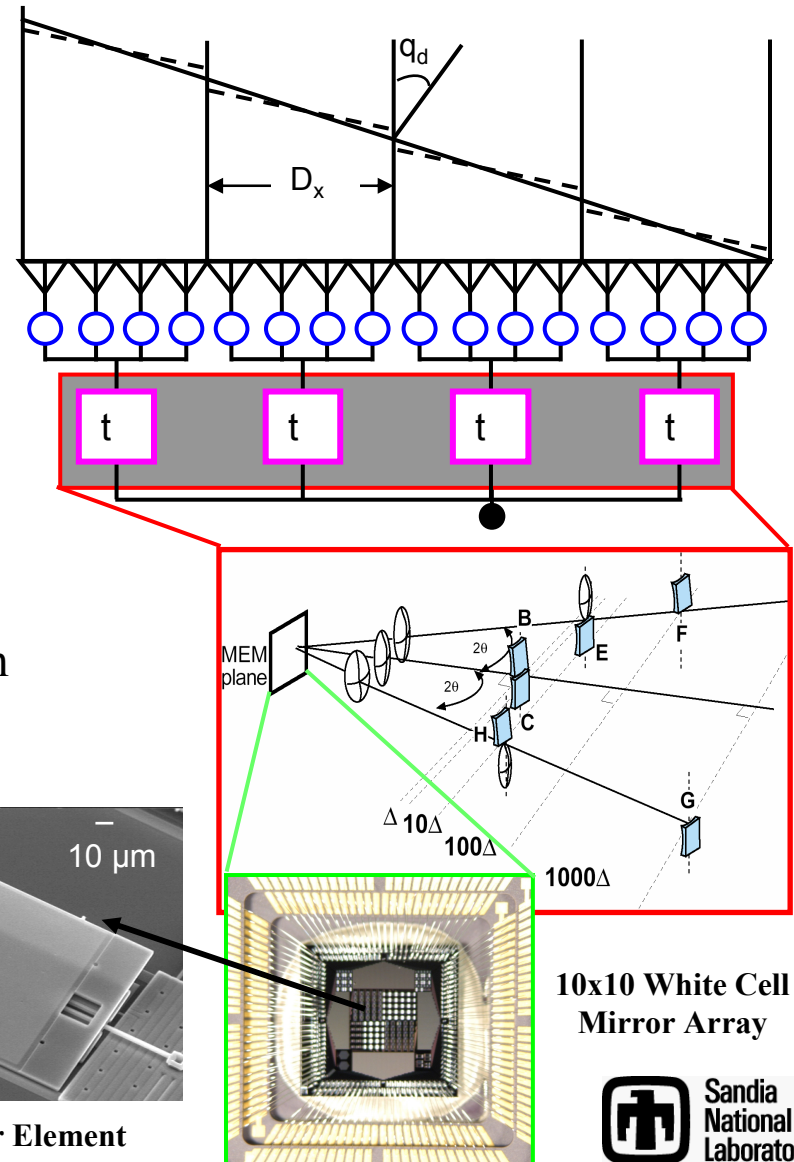** All PolySi is doped with Phosphorus **
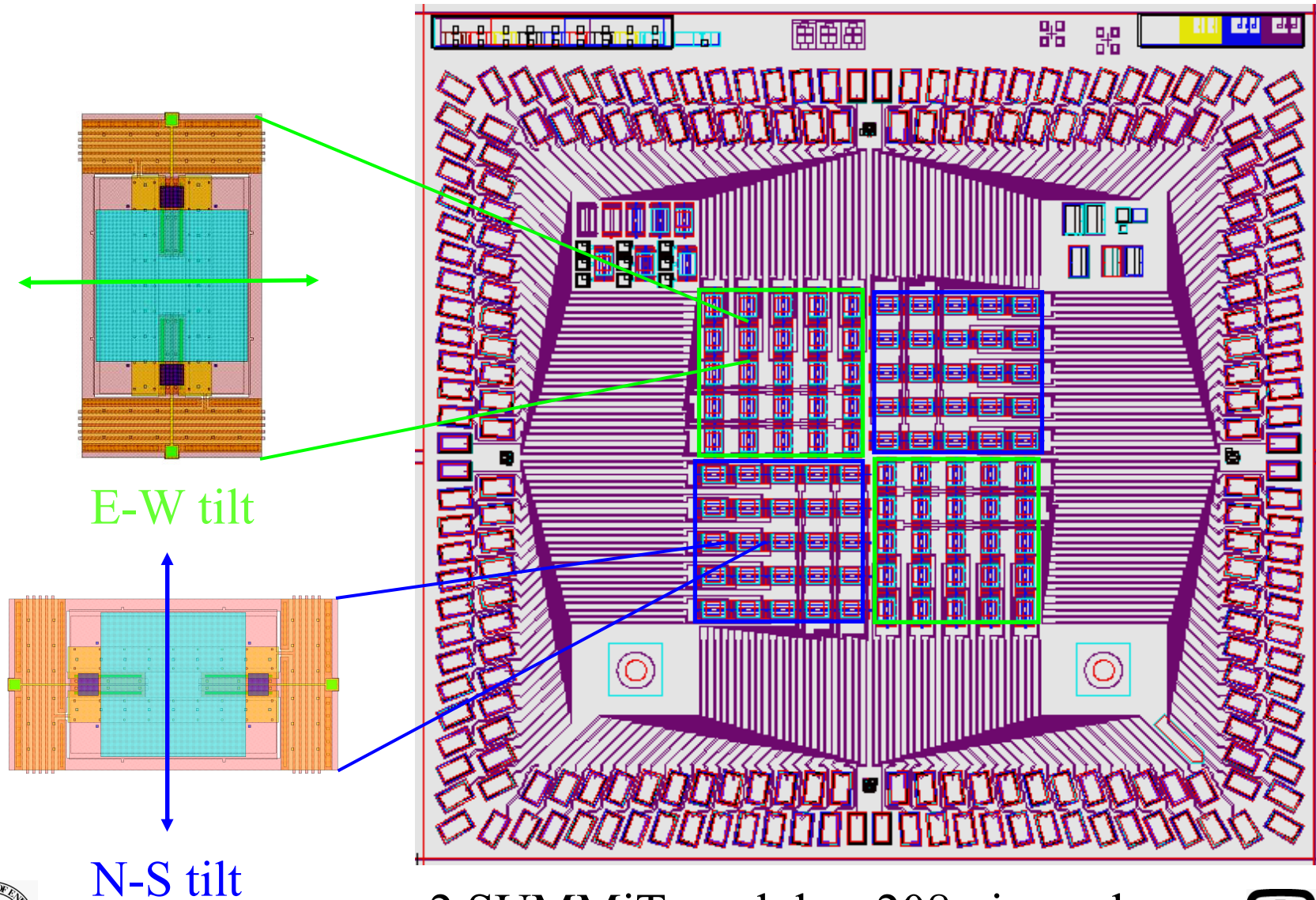
0.5 μm Dimple1 gap

Sandia Beamformer Technologies

- Several possible approaches (fiber, magneto optical switch etc…) to implementation of optical time delay
- MEMS approach offers highest payoff
  - Most hardware compressive
  - <6dB for 10-bit (revised to 6-bit) dc-20GHz (ultra low loss)
  - Delays of 0.3-30nsec
- Demonstrated performance
  - 10 μs switching for >100 μm mirror
  - Tri-stable operation (-10°, 0°, +10°)
  - 10^9 cycles without failure on packaged arrays
- System demonstration of selected time delays in 0.2 – 20 nsec range with 1.25 psec resolution (with OSU)

Hybrid Architecture Concept

218.3 μm

200.5 μm
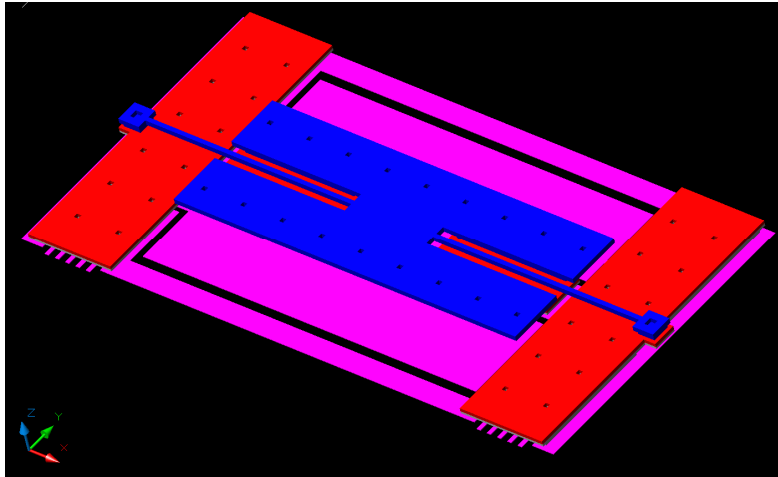
mm 19
2

0.0

-6.2

10 μm

SEM of Mirror Element

10x10 White Cell Mirror Array

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10x10 Mirror MEMS Array

E-W tilt

N-S tilt

2 SUMMiT modules, 208 pin package

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3-D view of the mirror

Mirror3, P0 through P3

Mirror3, P0 through Metal

P4 landing stub (1 of 4)

P0 electrode (1 of 2)

-10°   +10°
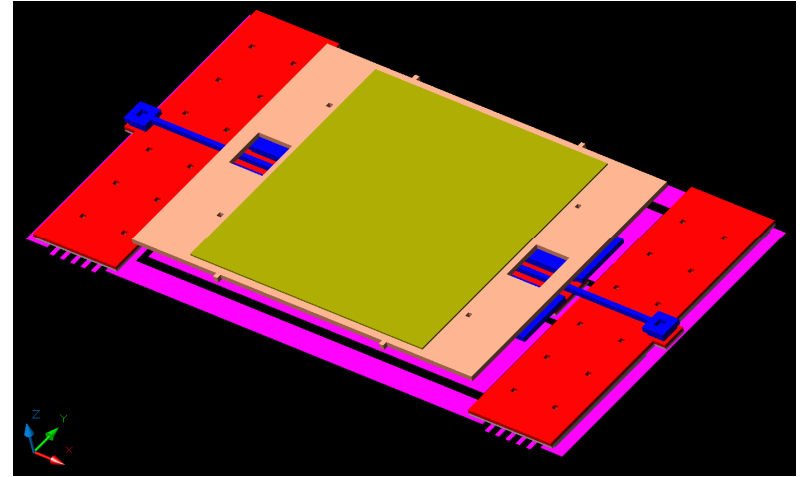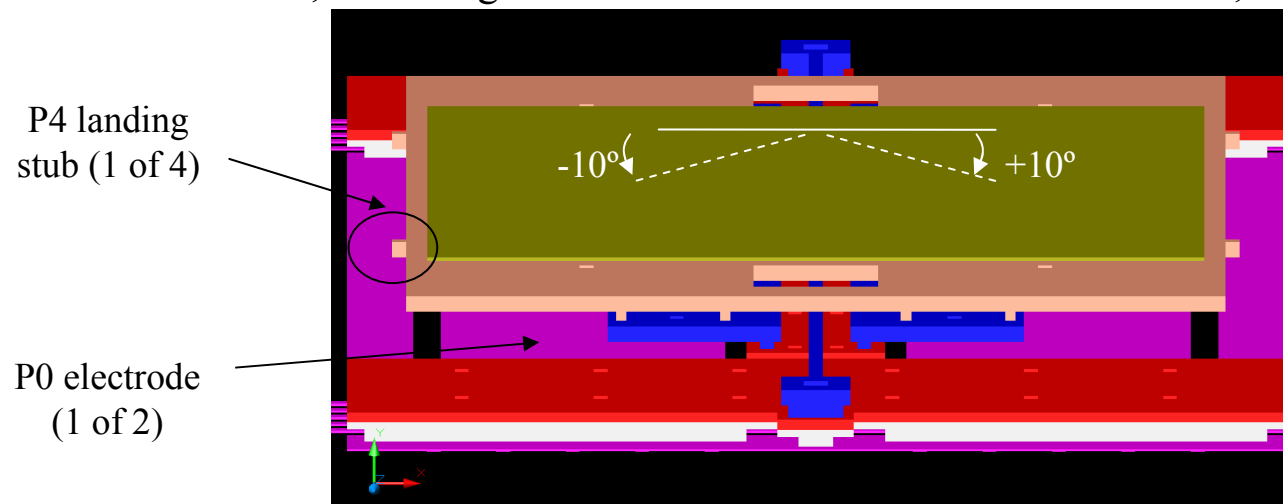
Mirror3 end view, P0 through Metal

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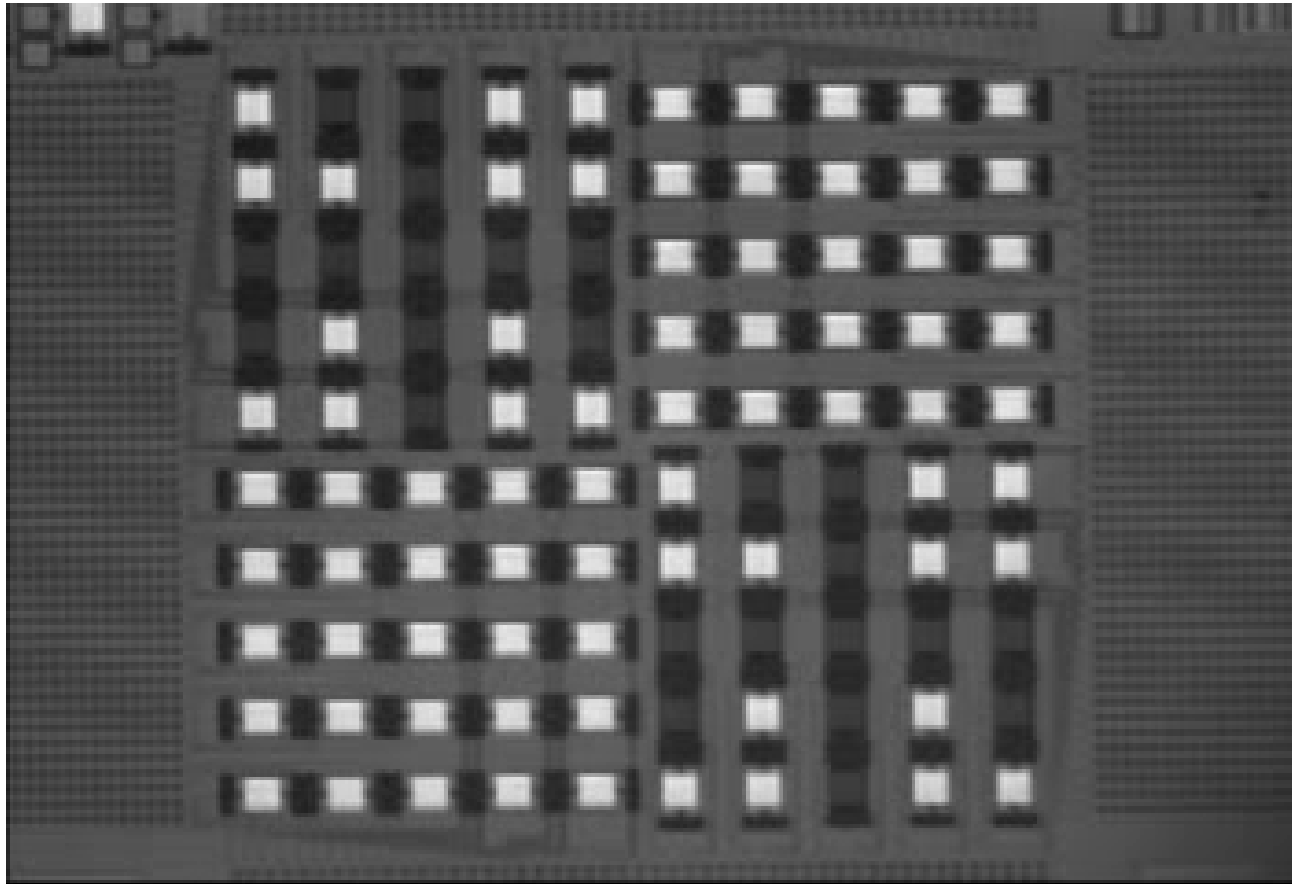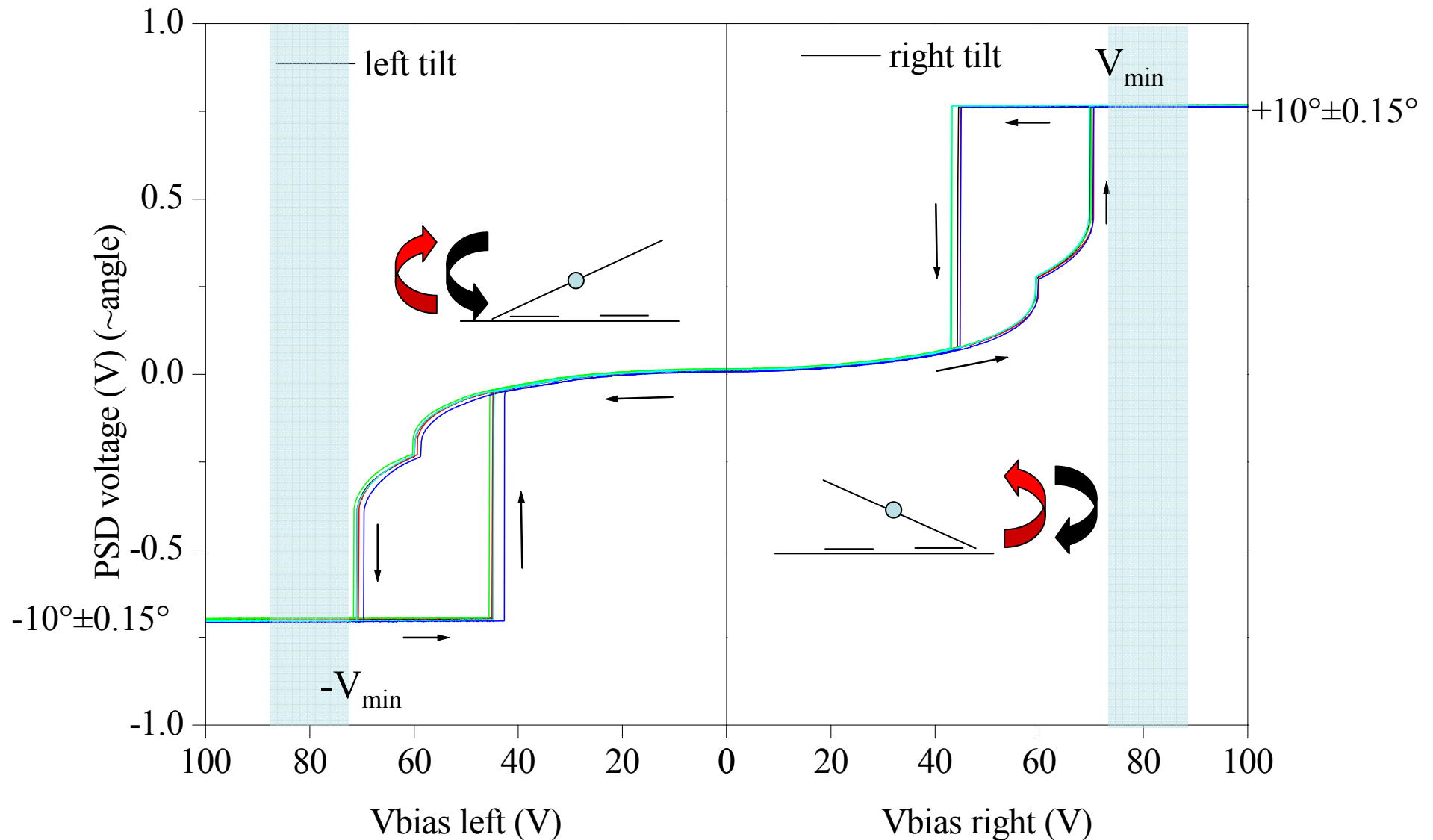
MEMS Array Image

Static Voltage Response of Five Mirrors
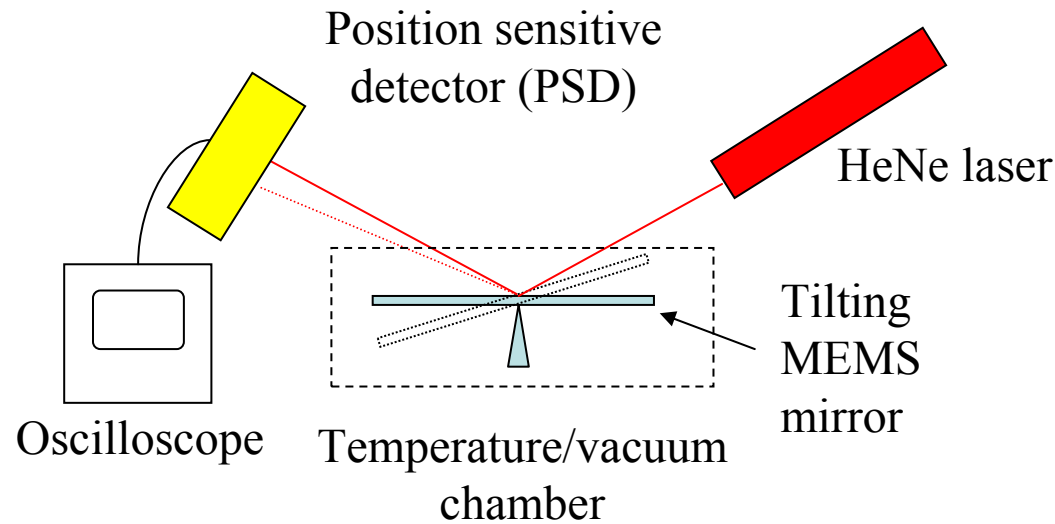

- Good uniformity between mirrors
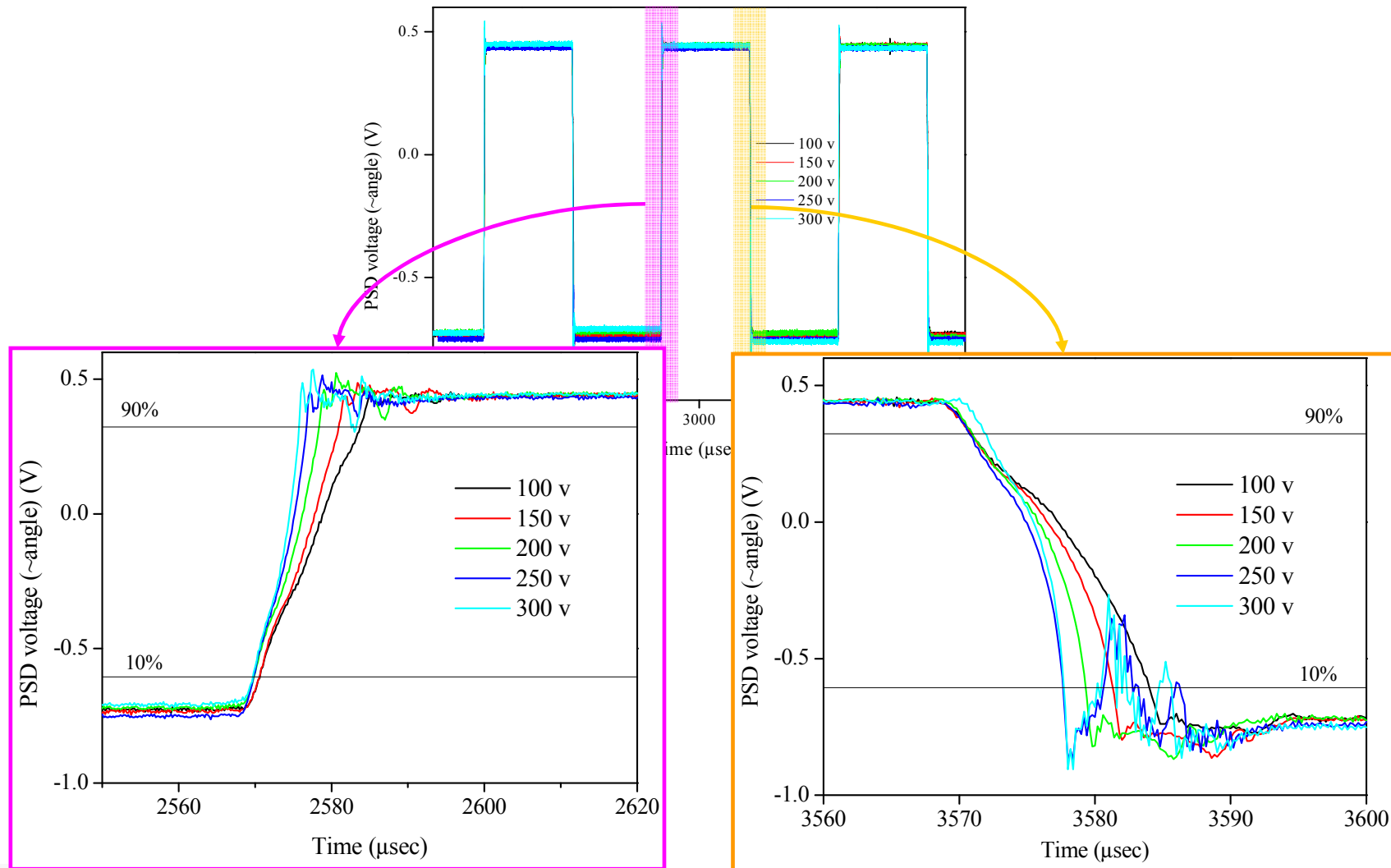- Hard stops at ±10° ensure insensitivity to bias voltage

Switching speed

- Switched bearing to bearing (-10º to +10º)
- Switching speed determined by time to traverse 10% to 90% of total angular swing
- Simple square waves applied to left and right pads 180º out of phase - nothing fancy
- Fastest response times most likely limited by unoptimized drive and detection electronics – new electronics underway

Position sensitive
detector (PSD)

HeNe laser

Tilting
MEMS
mirror

Oscilloscope

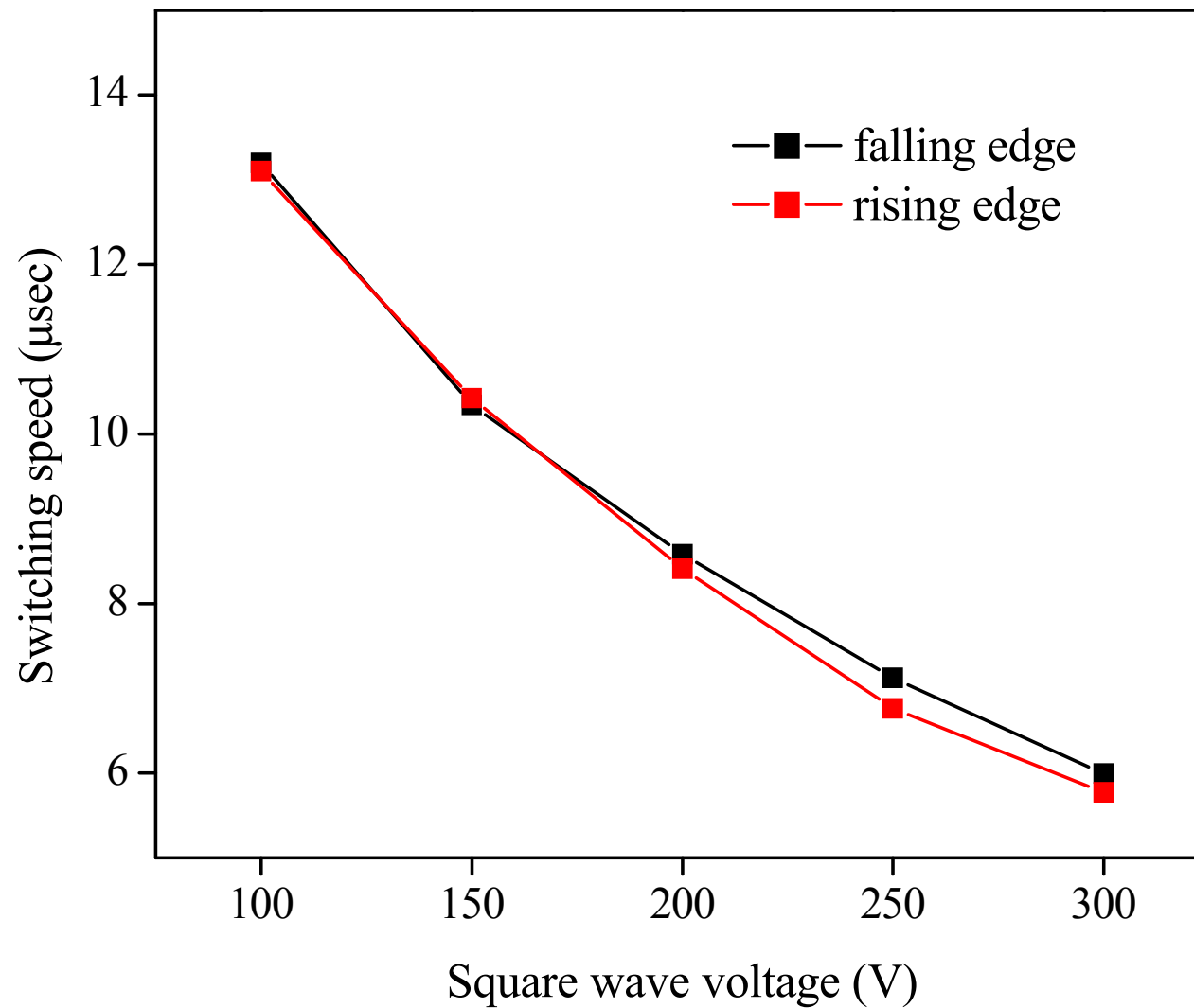Temperature/vacuum
chamber

Bearing to bearing switching speed (-10º to +10º)

Driven by square waves of increasing amplitude

Switching speed vs. applied bias

# Modified vs. standard waveforms

Drive voltage (unamplified) (a.u.) vs Time (μsec)

- ch0 (modified waveform)
- ch0 (standard waveform)
- ch1 (modified waveform)
- ch1 (standard waveform)

Refinements in switching speed

- Switch 10º to 0º - problem with ringing at 0º
- Electrostatic damping to remove ringing (modified vs. standard waveforms)

PSD voltage (~angle) vs Time (μsec)

- tailored waveform (10 μsec switch time)
- standard waveform (19.4 μsec switch time)

- Different switch structure: switch angles -2.5º to +2.5º
- Also possible bearing to bearing switching with soft landing – hit the substrate at 0 velocity without sacrifice in switching speed

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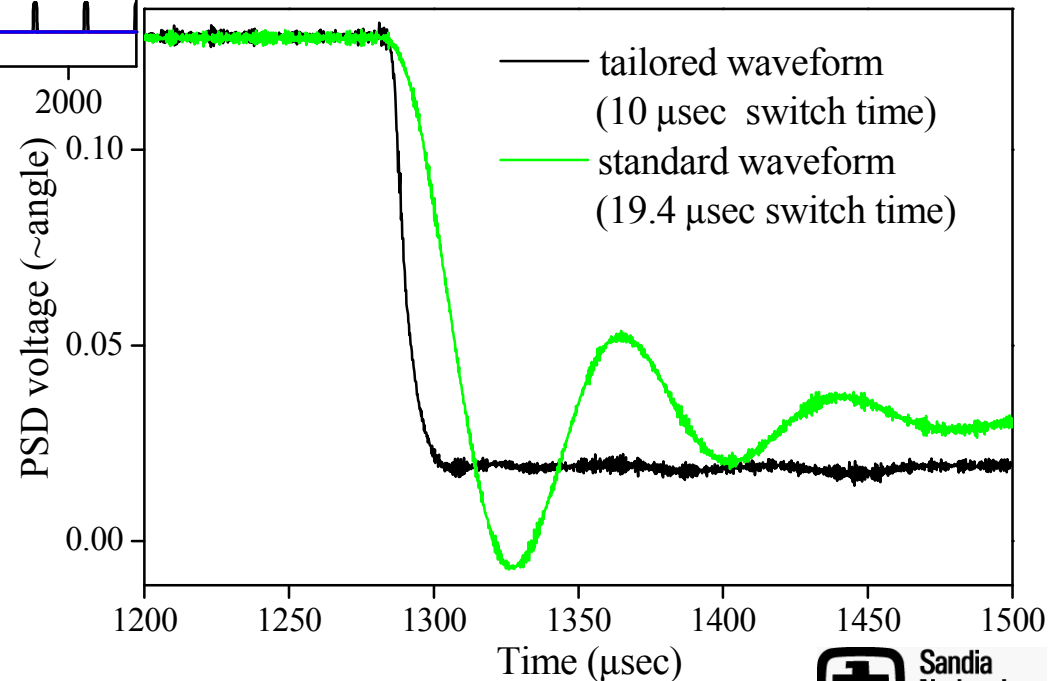
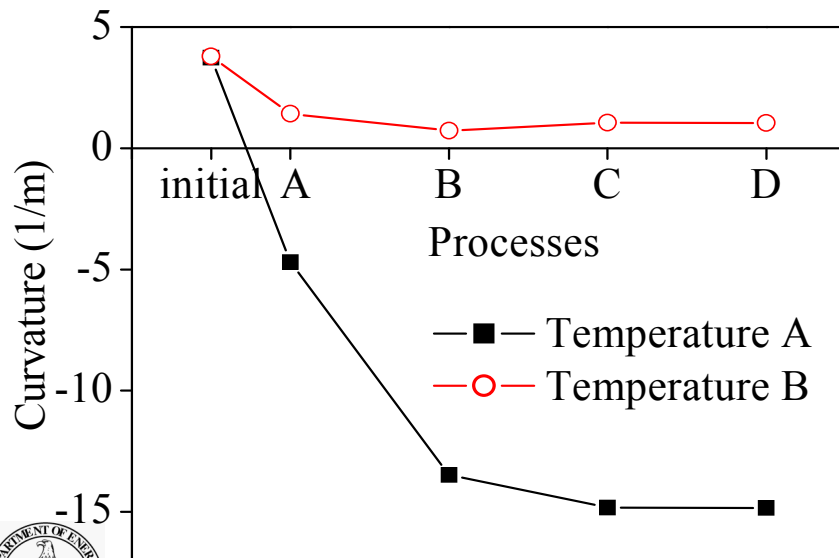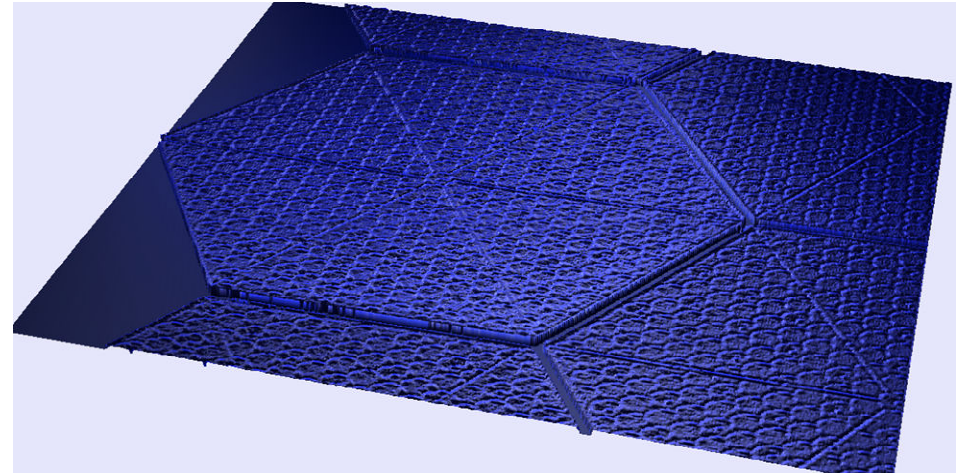# Surface Quality of Mirrors

100 nm Al

50 nm Au
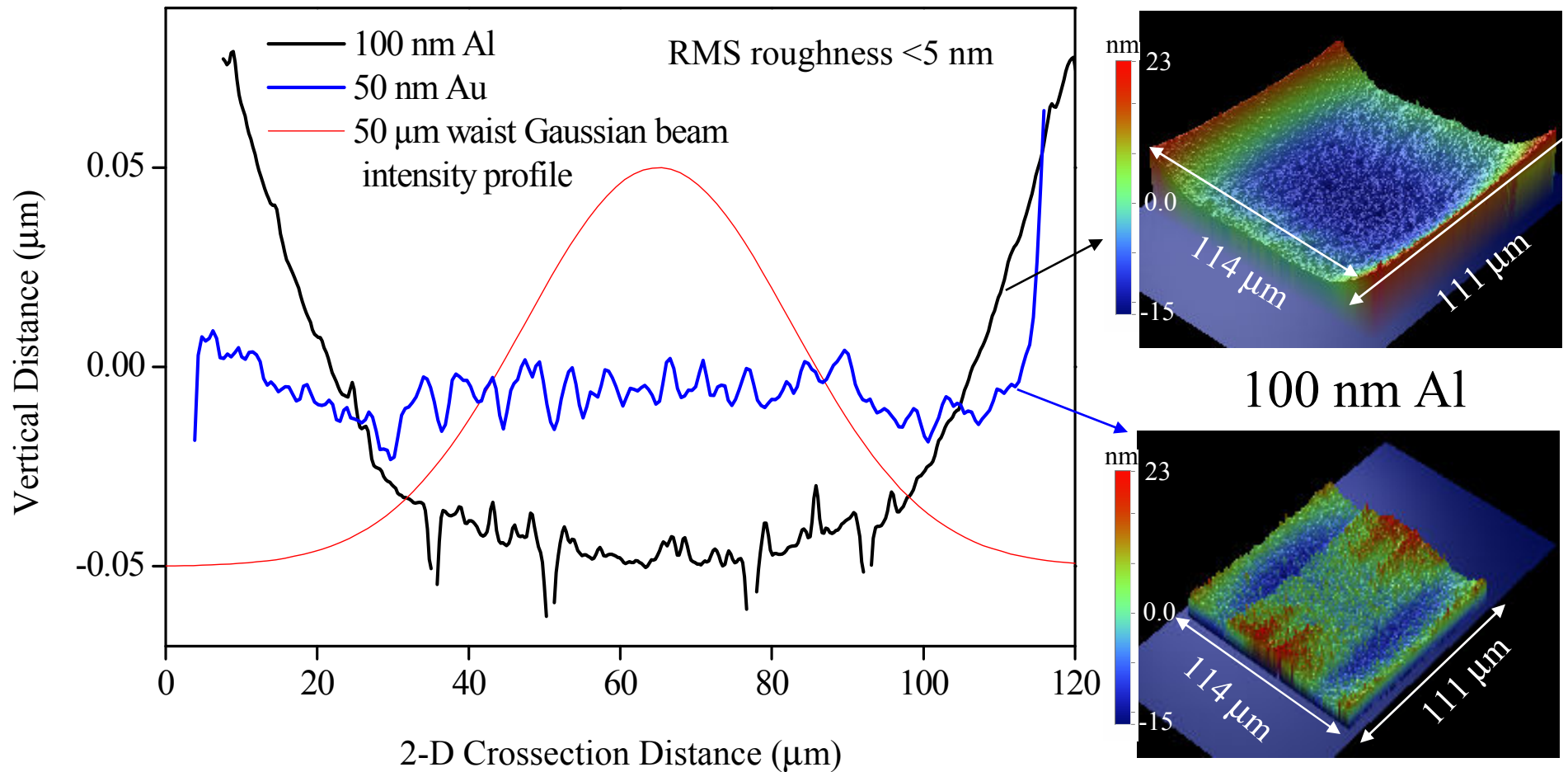
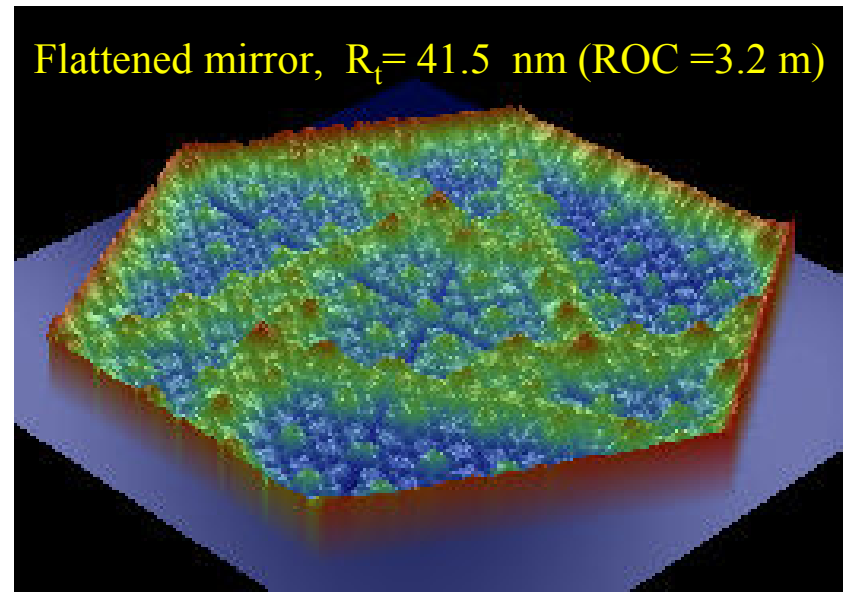• Characterized mirror surfaces to predict the impact on system performance
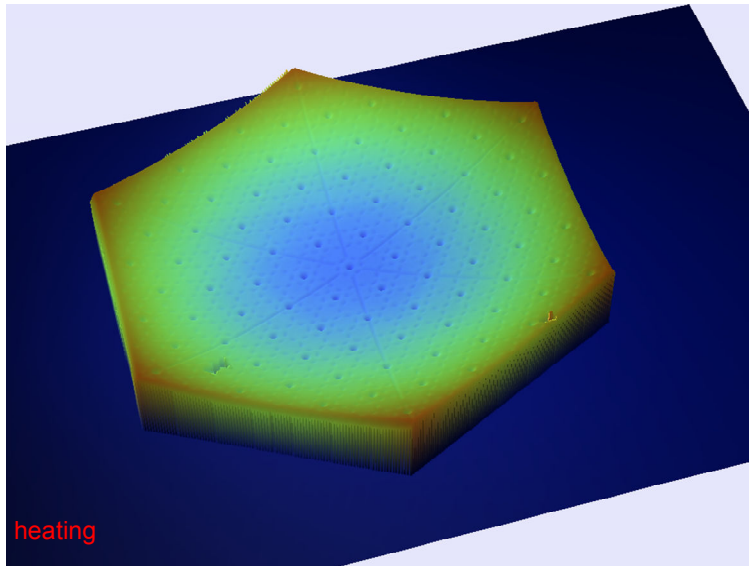
Mirror Surface Quality

Initial   Process A

Process B   Process C

Curvature (1/m)

Processes

initial A   B   C   D

- ■ Temperature A
- ○ Temperature B
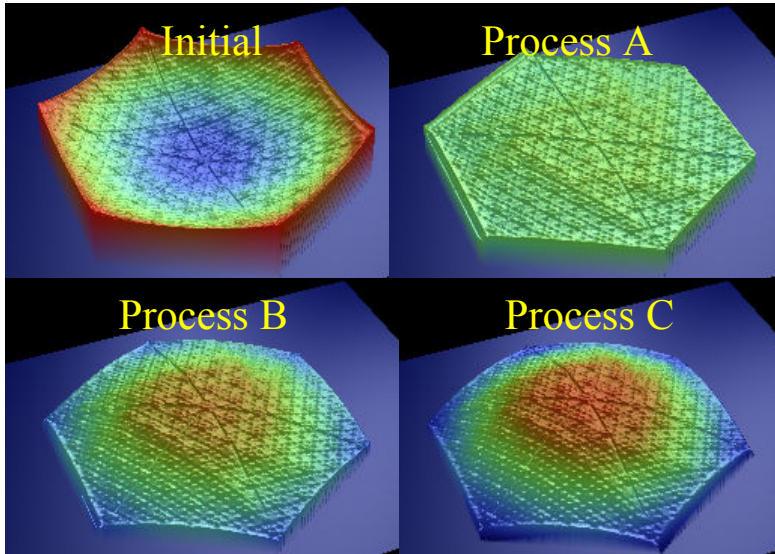
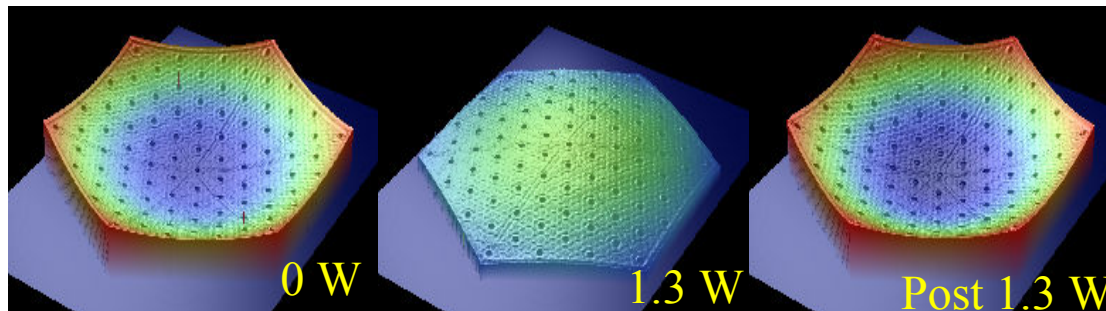Flattened mirror, R_t = 41.5 nm (ROC = 3.2 m)

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Temperature and high optical power effects

Ambient heating

WYKO

WYKO "through-glass" interferometric objective

Multi-layer polysilicon mirror

Si

Heater Element

Vacuum chamber with heater/cooler (-80K to 780K)

0 W   1.3 W   Post 1.3 W
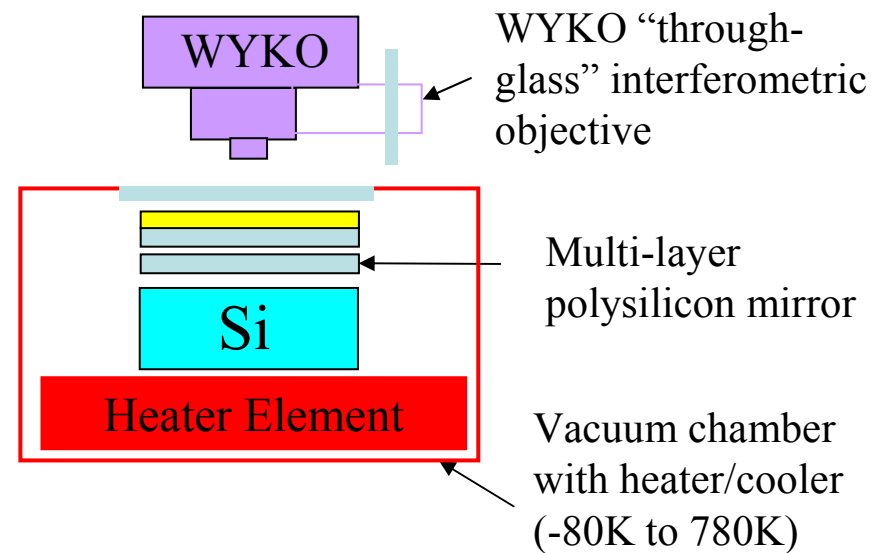
Laser heating   (1.3 W → 2.8 kW/cm²)

nm
754
0
-580

WYKO

1.3 W of 808 nm light in a 100 μm core fiber

Si

Multi-layer polysilicon mirror

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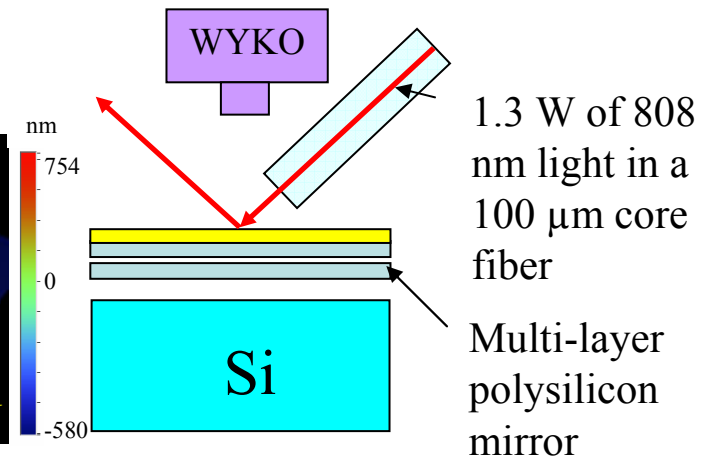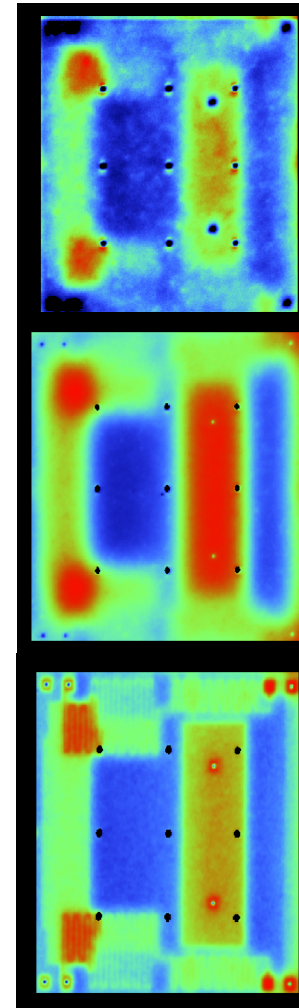
Influence of mirror roughness
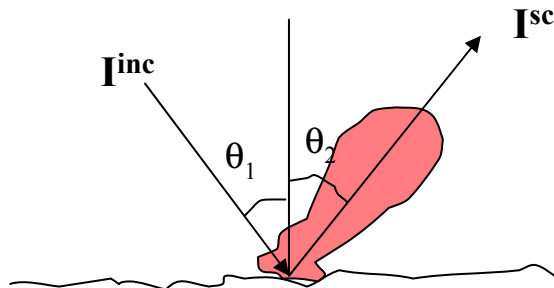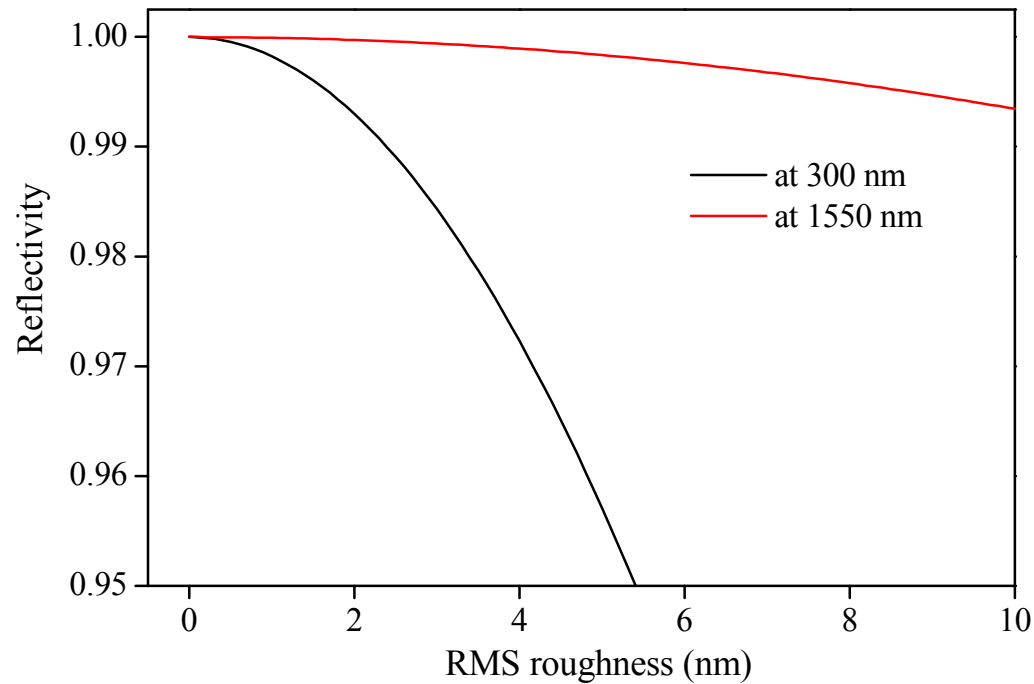
$$\langle I_{sc} \rangle = I_0 e^{-(4\pi\sigma\cos\theta_1/\lambda)^2} + \langle I_d \rangle$$
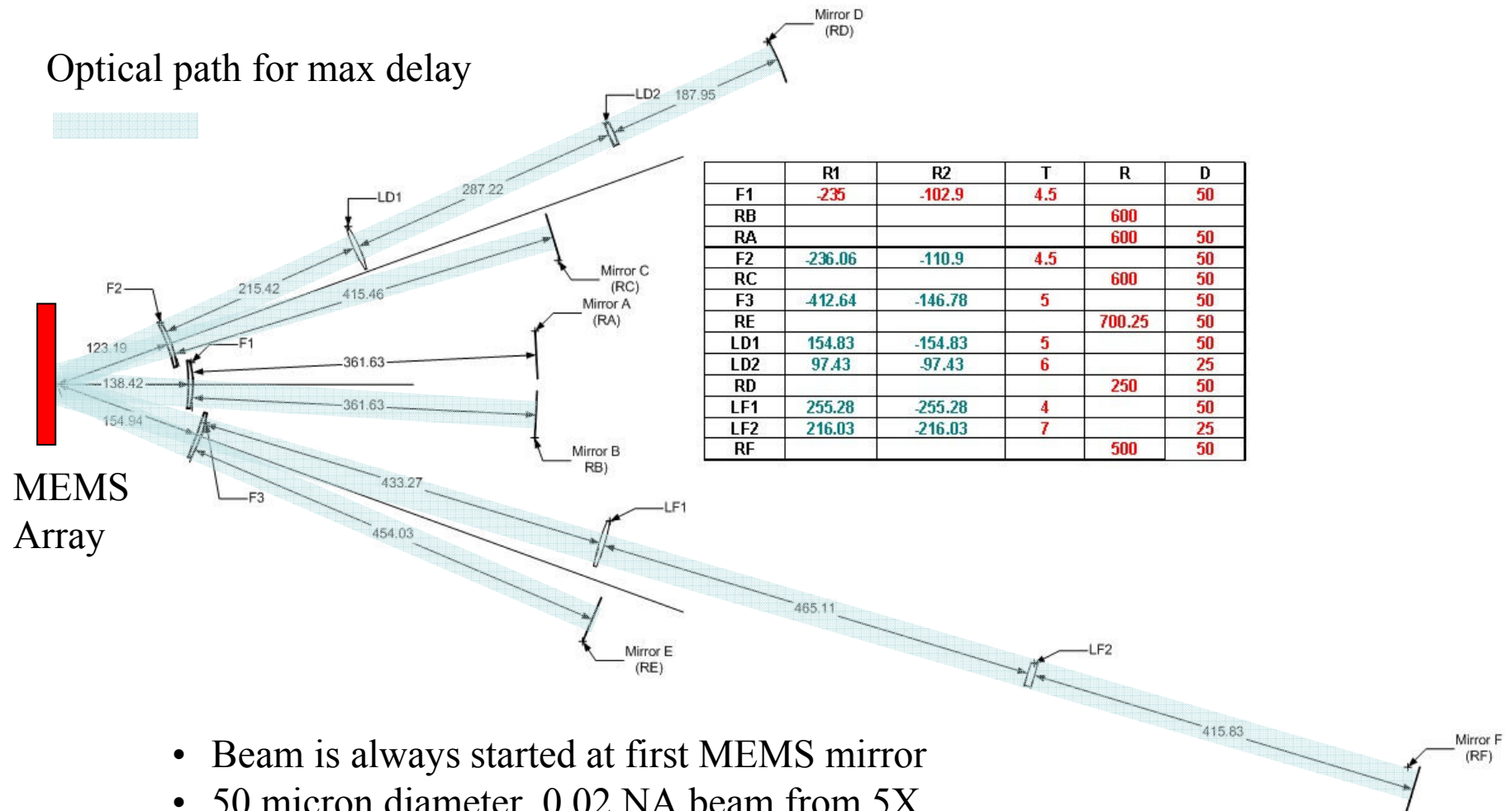
Rq=2.43 nm

Rq=14.95 nm

Rq=19.6 nm

Effect of process modification

Starting point for quartic cell model

Optical path for max delay

MEMS Array

	R1	R2	T	R	D
F1	-235	-102.9	4.5		50
RB				600	
RA				600	50
F2	-236.06	-110.9	4.5		50
RC				600	50
F3	-412.64	-146.78	5		50
RE				700.25	50
LD1	154.83	-154.83	5		50
LD2	97.43	-97.43	6		25
RD				250	50
LF1	255.28	-255.28	4		50
LF2	216.03	-216.03	7		25
RF				500	50

Mirror D (RD)
LD2   187.95
LD1   287.22
Mirror C (RC)
Mirror A (RA)
F2   215.42
415.46
123.19
F1
361.63
138.42
361.63
154.94
Mirror B RB)
F3
433.27
454.03
465.11
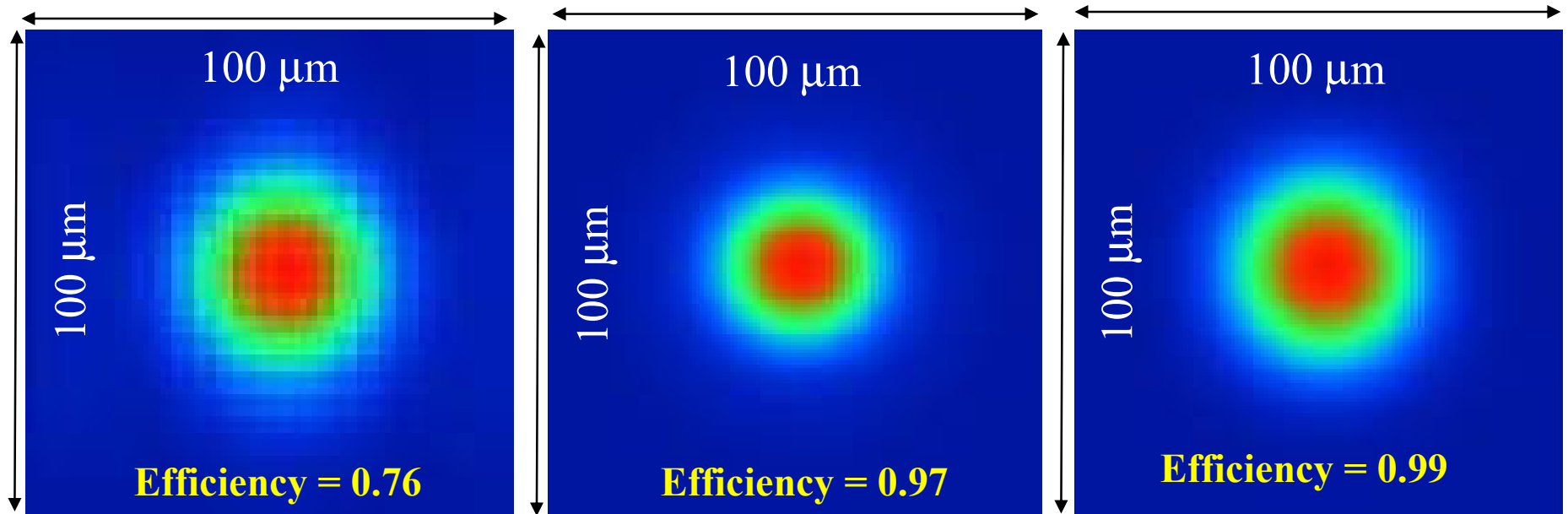Mirror E (RE)
LF1
LF2
415.83
Mirror F (RF)

- Beam is always started at first MEMS mirror
- 50 micron diameter, 0.02 NA beam from 5X magnification of 10 micron, 0.10 NA fiber
- Wavelength is 1.55 microns

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ZEMAX™ Model of White Cell

Modeled spot on the last MEMS mirror after acquiring maximum optical delay 10 bounces on MEMS mirrors

Optics aberrations only
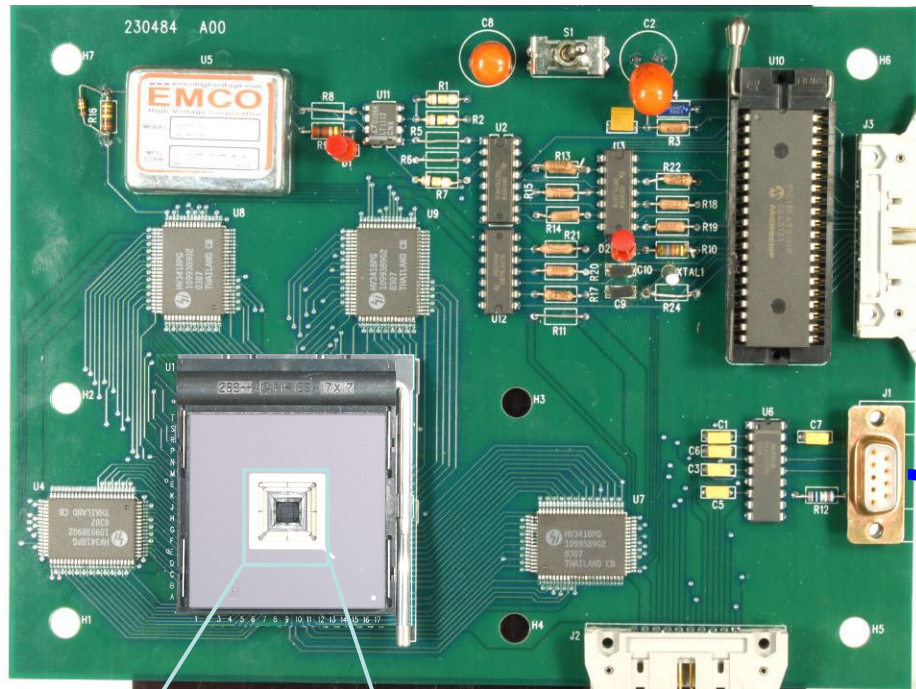(Ideal MEMS mirrors)

Al metallized MEMS
aberrations only
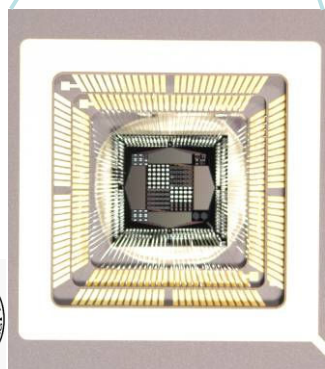
Au metallized MEMS
aberrations only

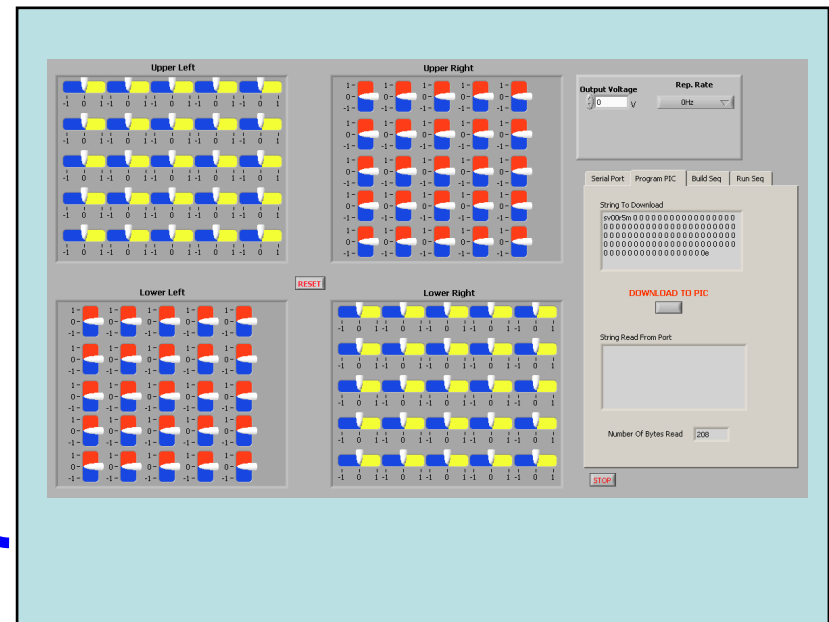# MEMS Package, Drive Electronics and Control Software

Research prototype drive electronics board
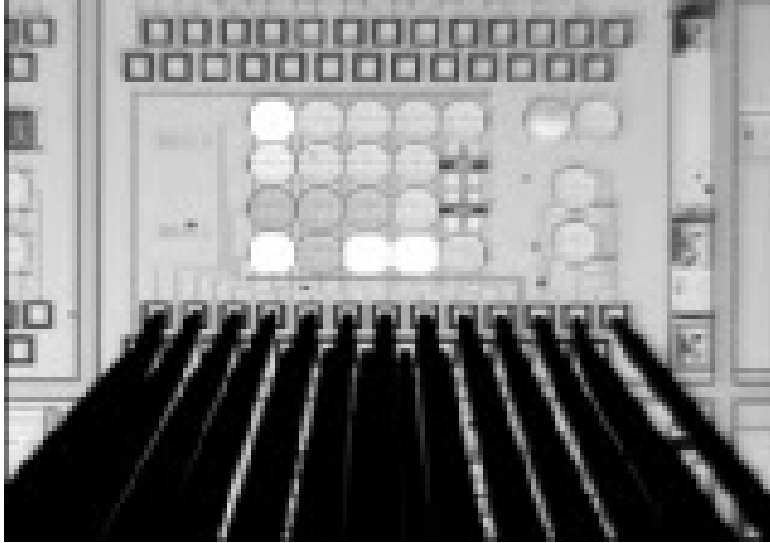
RS232

Control software

MEMS chip packaged in a 208 pin PGA

A complete optical subsystem for laboratory demonstration

MEMS/SFET Integration

SFET driven mirror array (movie)

- **Poly0 (gate)**
- **MEMS polysilicon**
- **Oxide**
- **p-type substrate**
- **N+ source & drain**
- **3x4 SFET mirror array w/ 3 transistors per cell**
- **SUMMiT FET cross-section**
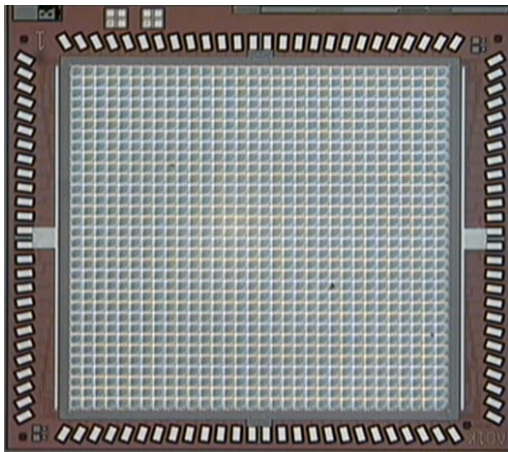
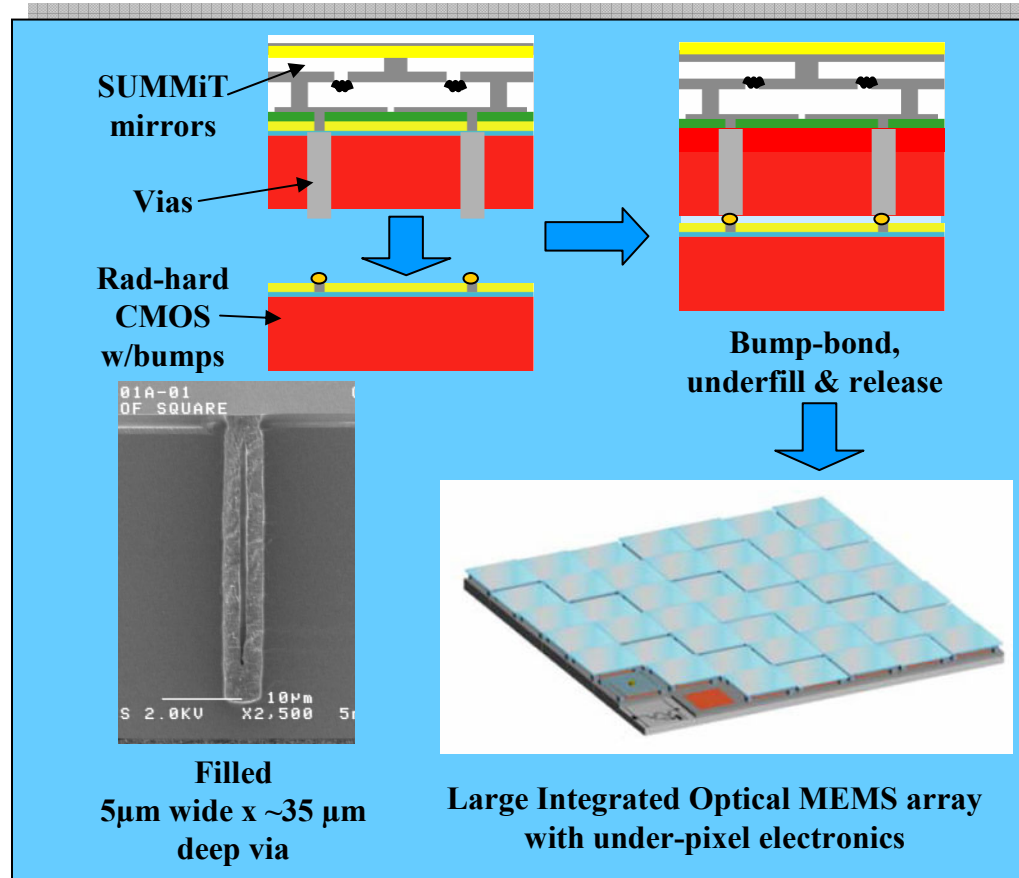SFET driven 32x32 piston mirror array for AO
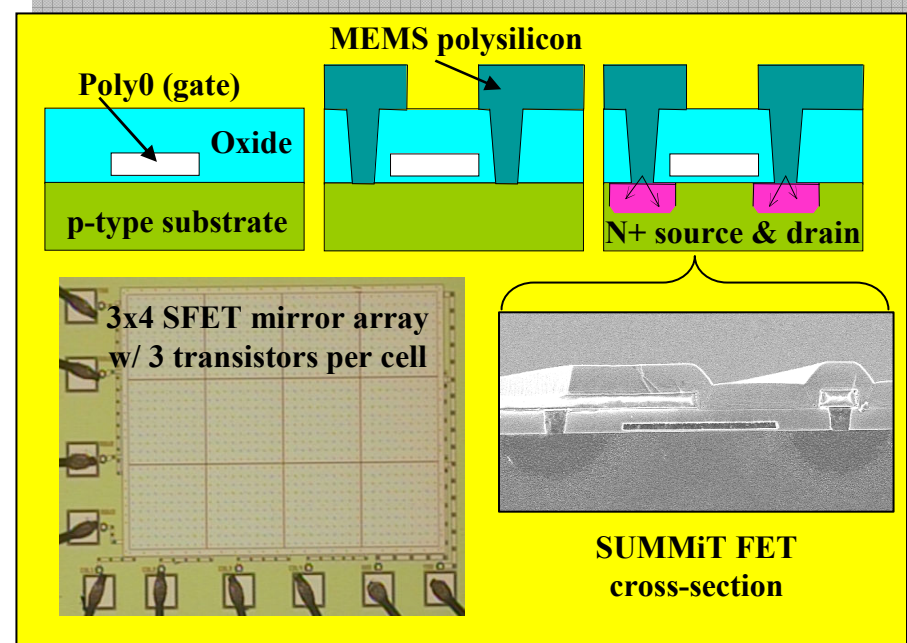
- SFET (SUMMiT FET)
  - WFO supported as risk mitigation task
  - Goal: SUMMiT OMEMS w/ integrated NMOS electronics
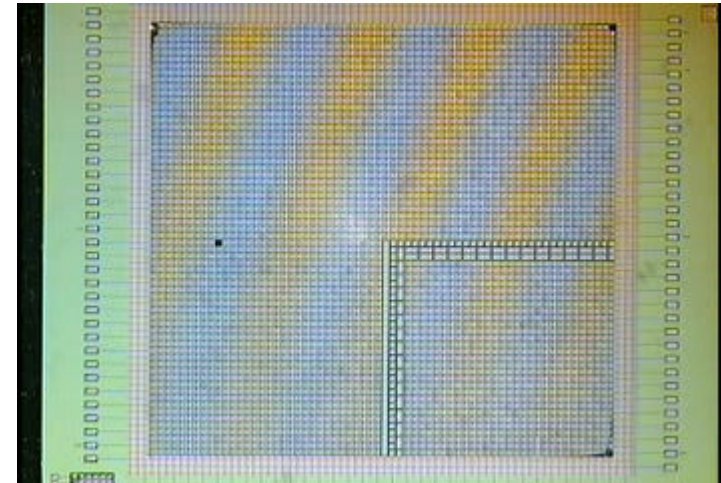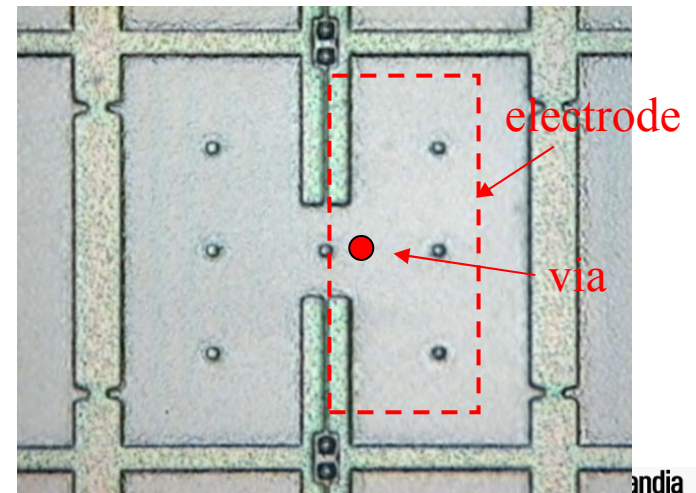 - Demonstrated actuation of 12 and 20 mirror arrays, scale up to 1600 element array (40x40) for brass board demo

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Heterogeneous integration: vias

SUMMiT mirrors

Vias

Rad-hard CMOS w/bumps

Bump-bond, underfill & release

Filled
5μm wide x ~35 μm deep via

Large Integrated Optical MEMS array with under-pixel electronics

Movie of tilting mirror array interconnected by 4096 vias

electrode

via

Individual tilting mirror

- Goal: 4096 SUMMiT mirrors w/vias bump bonded to underlying electronics
- Demonstrated actuation of 4096 mirrors with linked vias

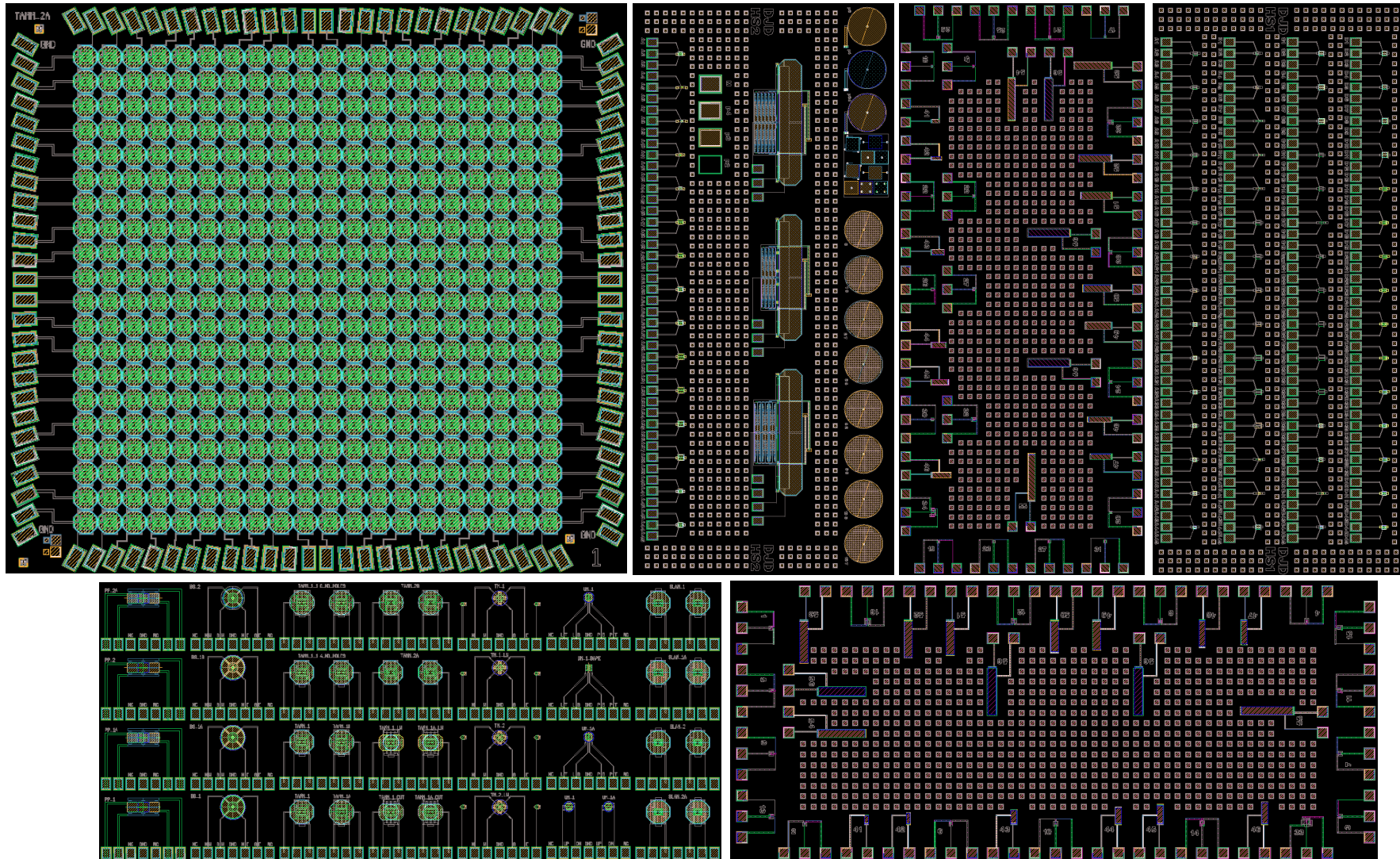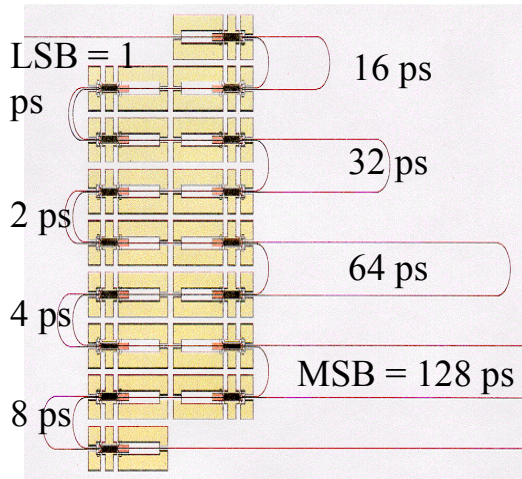Sandia National Laboratories

Faster MEMS mirrors designs

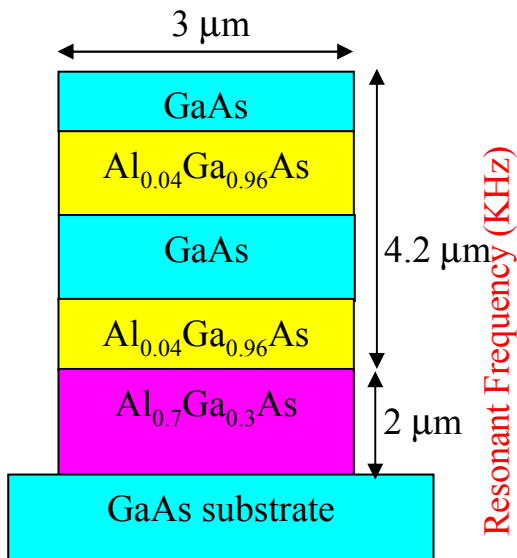Mirrors varying from 20-250 mm, angles 1.5º-2.8º, designed for speeds 0.1 – 100 μsec

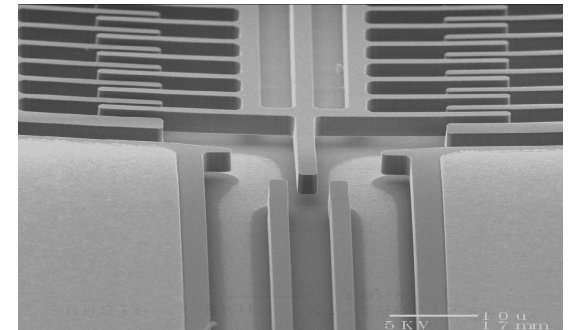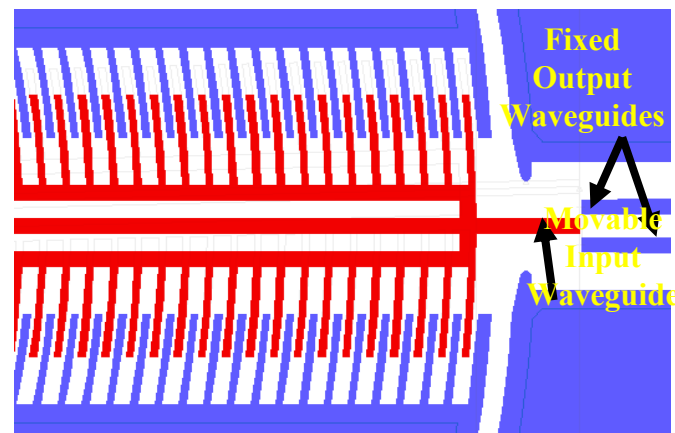# Compound semiconductor waveguide MEMS

LSB = 1 ps

16 ps

32 ps

2 ps

64 ps

4 ps

MSB = 128 ps
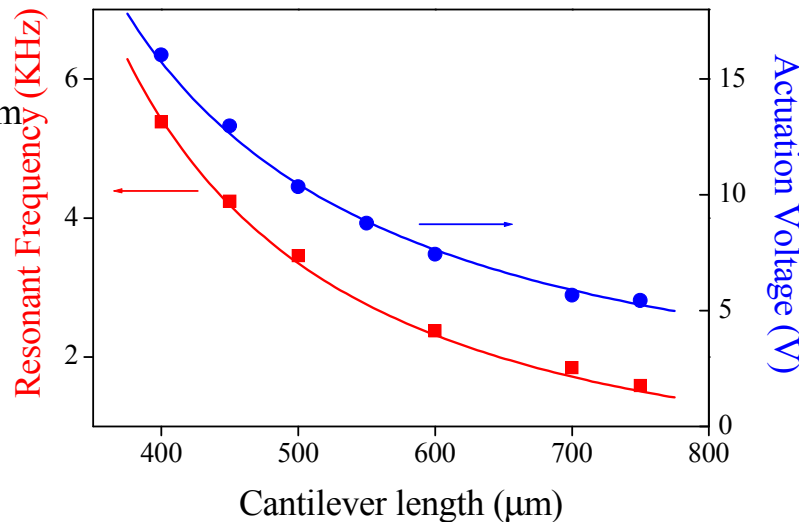
8 ps

Applications: optical time delay, optical sensors, on-chip signal routing and multiplexing (especially if monolithically integrated with lasers and detectors)

Fixed Output Waveguides

Movable Input Waveguide

3 μm

| GaAs |
| $Al_{0.04}Ga_{0.96}As$ |
| GaAs |
| $Al_{0.04}Ga_{0.96}As$ |
| $Al_{0.7}Ga_{0.3}As$ |
| GaAs substrate |

4.2 μm

2 μm
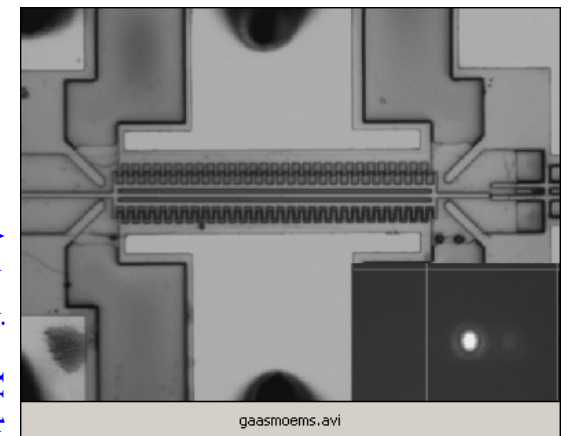
Cantilever cross section

Resonant Frequency (KHz)
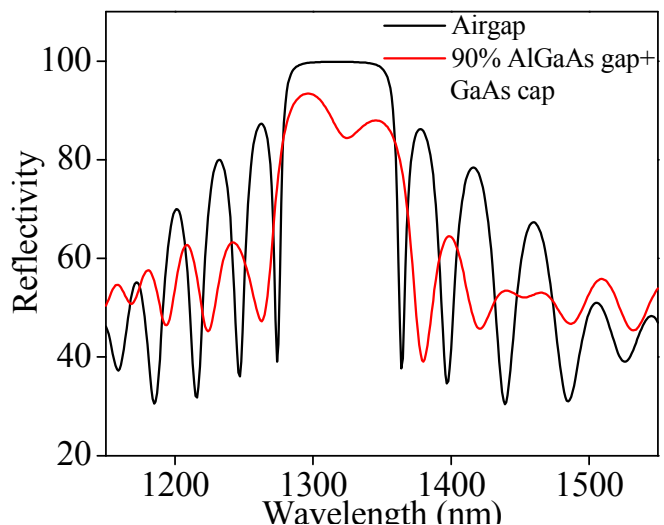
Actuation Voltage (V)

Cantilever length (μm)

Waveguide Switch
- $T_{switch} \sim 50 \mu sec$ (350 μm guide)
- switch loss =0.8 dB (w/o insertion loss)
- 4 V< bias <12 V

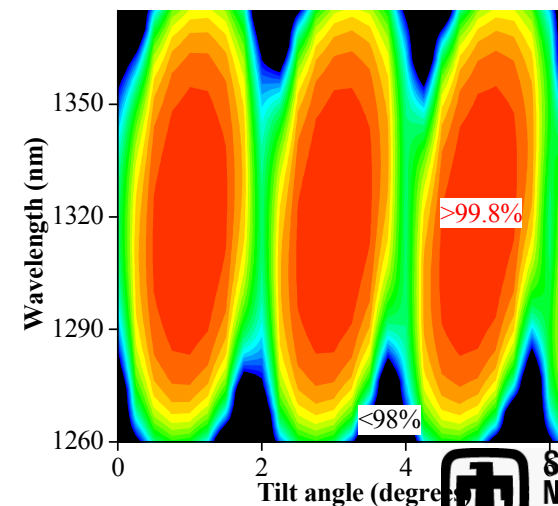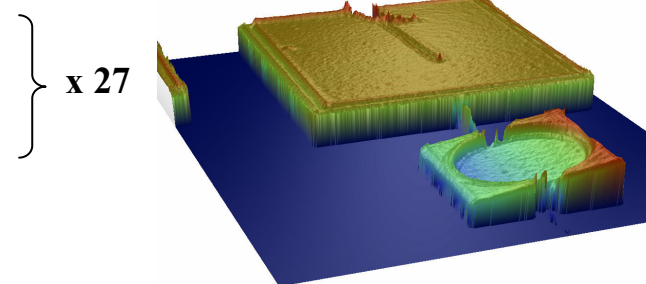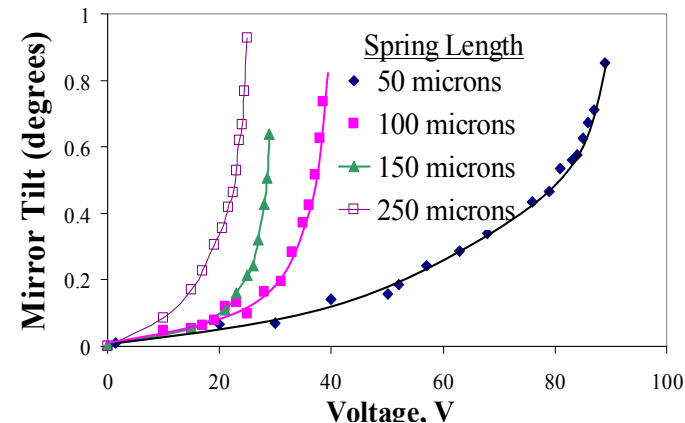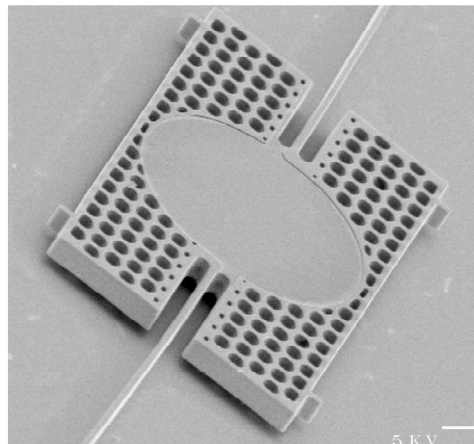gaasmoems.avi

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Compound semiconductor surface normal MEMS

High Reflectivity Tilt Mirror (HiRTM)

- Designed for R>98% for all angles
- Tilt angle ~ ±3.4°
- Predicted tilt bias 15>V>5 for 300 μm long springs

GaAs 1000 Å, n 2e19
$Al_{0.45}Ga_{0.55}As$ 2078 Å
GaAs 968 Å
$Al_{0.5}Ga_{0.5}As$ 1047 Å
GaAs 968 Å
$Al_{0.9}Ga_{0.1}As$ 23080 Å
GaAs substrate n^+

} x 27

Conclusion

- Sandia is involved in a variety of optical MEMS programs
- Existing surface micro-machined MEMS mirrors switch in 10 µsec
  - New designs for faster switching speeds (<0.1 µsec) currently in fab
  - Advanced control algorithms for enhanced switching speeds and dynamic control have been implemented
- High reflectivity MEMS mirrors possible, but challenging for UV wavelengths
  - Mirror figure can be controlled by post-processing techniques
  - Mirror roughness can be controlled by appropriate process modifications
- Modeling of optical micro system performance including MEMS non-idealities
- Drive electronics and control software for large numbers of independent high voltage channels available
  - Interconnect scale-up problem currently being addressed by integrated electronics and by via approaches
- Advanced integration schemes involving MEMS in compound semiconductor materials promise the ultimate in monolithic integration: sources, detectors and MEMS on a single chip

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MEMS do pop out of plane!